Total Dose Testing Methodology for Bipolar Circuits Operating in the Jovian Radiation Environment

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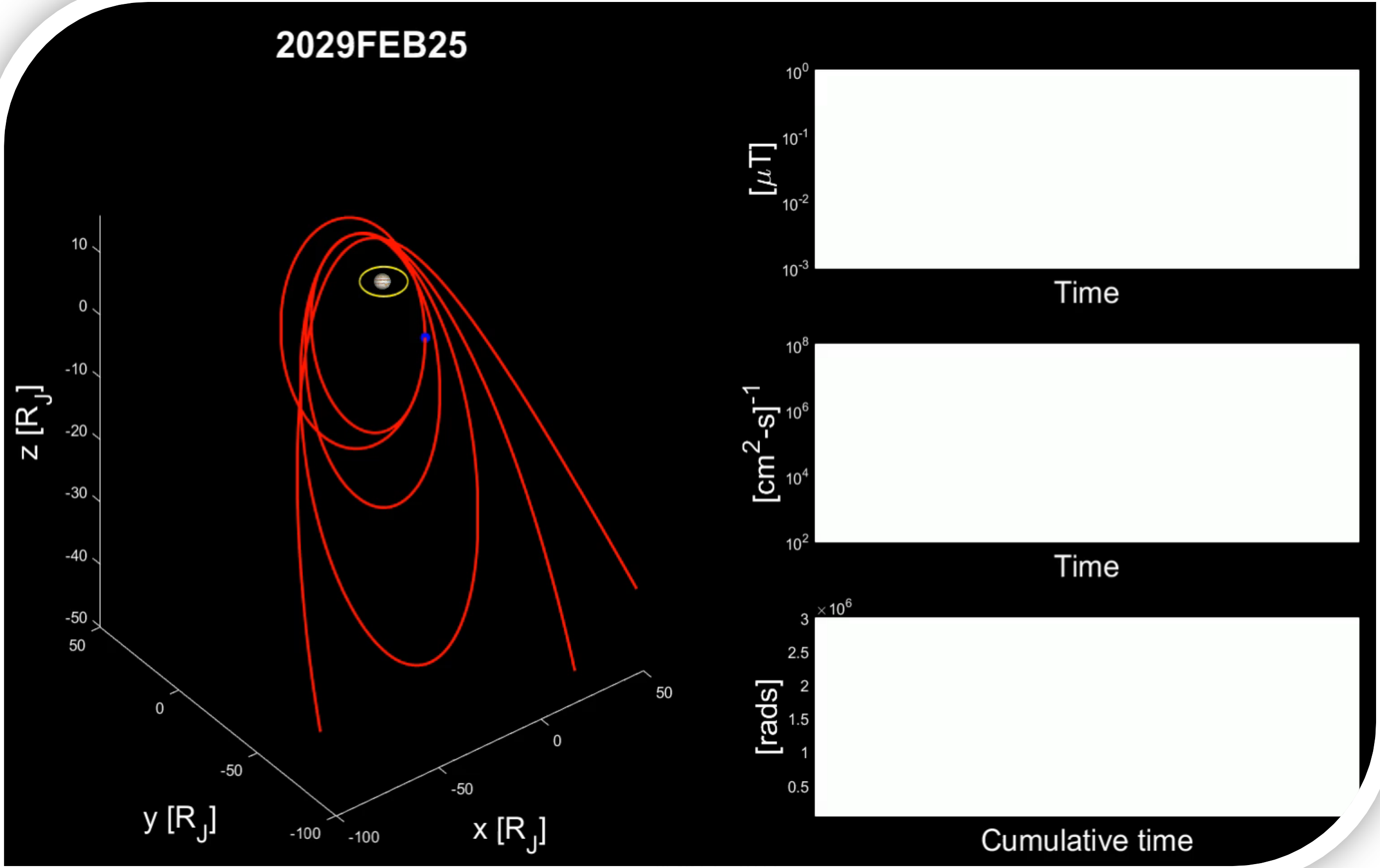
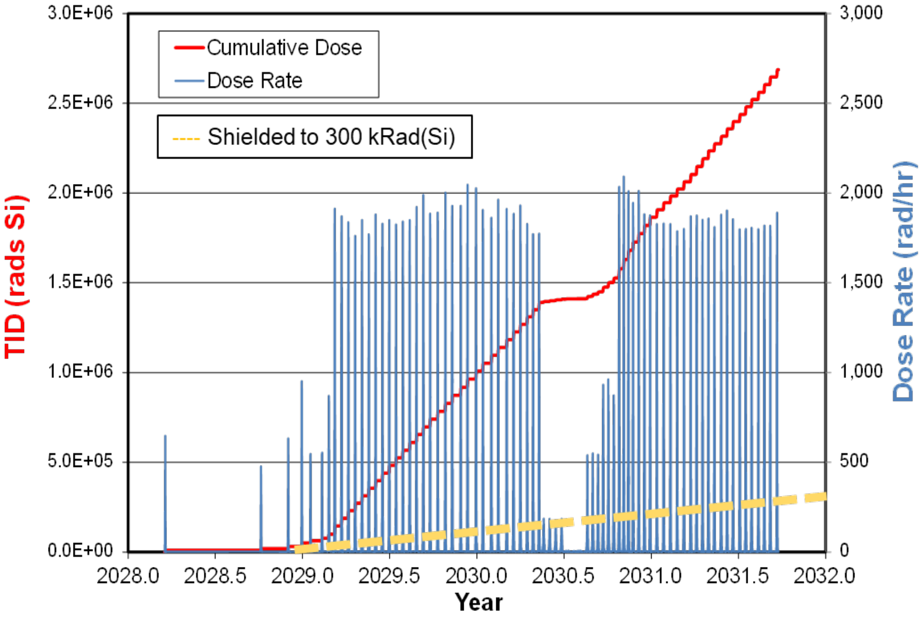
Context

- The Europa Clipper (EC) Mission will operate in a very severe radiation environment (~300 kRad(Si) after shielding) compared to standard space missions
- The standard test procedure to bound the performance of circuits subject to ELDRS is MIL-STD-883, Test Method 1019 condition D
  - This method requires testing at < 10 mRad(Si)/s for bipolar parts
- The challenge with EC is that performing testing RLAT at a dose rate of 10 mRad(Si)/s to 300 kRad(Si) will take about one year to complete
  - **<u>This is simply not practical.</u>**
- We propose a radiation hardness assurance test method built on EC mission dose profile that reduce qualification test time from 1 year to 80 days

Radiation Environment for Europa Clipper Mission

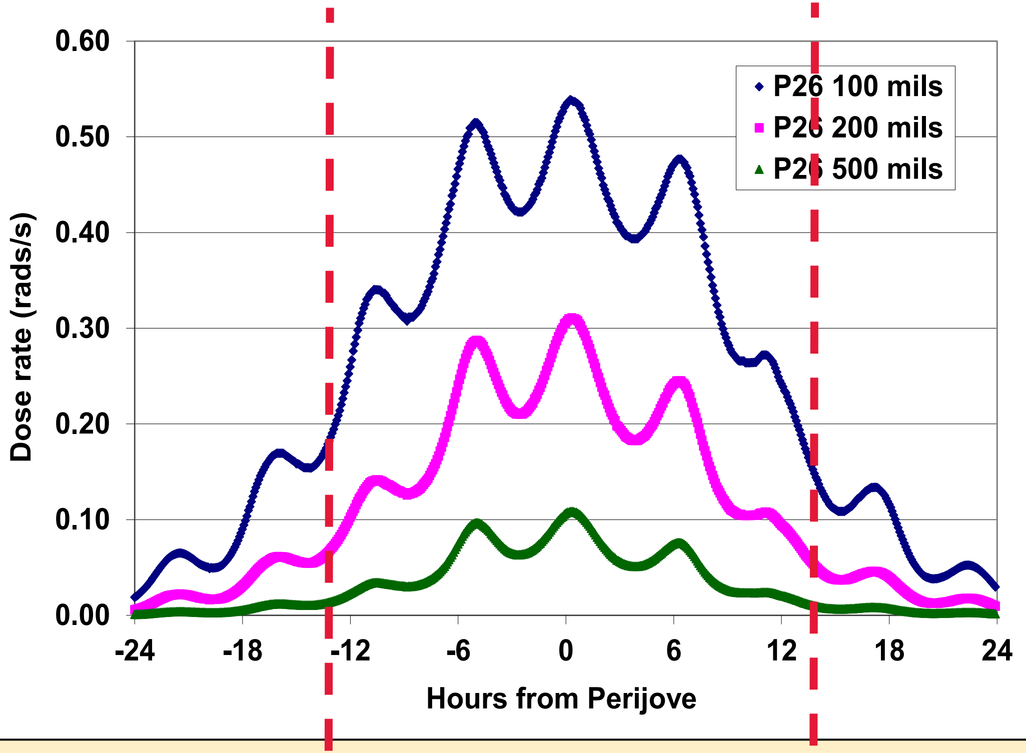


Mission Dose Profile



- Performing many flybys using elliptical orbits to be in and out of Jupiter radiation belts
  - 48 hours flybys
  - 10-12 day period outside radiation belts
- The spacecraft "vault" is heavily shielded and contains most sensitive electronics
- The dose inside the "vault" is reduced to 150 krad (behind 500 mil of Al)
- The mission dose cap (behind 100 mil of Al) is 3 Mrad(Si)
- Mission requirements use RDF of 2

Dose Rate at Flyby



For 500 mil and up, 90% of dose accumulates between -13 and +13 hours
Corresponds to about ~80 days of accumulated dose

Parts selected for the study

Part Number	Procurement	Mfr	Type	Date Code	Package
LM124	RM124AJRQMLV	TI	Op-Amp	H7B1032R	14P CERDIP
LM2941	RM2941JXQMLV	TI	Regulator	H9A0911F	16P CERDIP
LM136	RM136AH2.5RQMLV	TI	Voltage Reference	1105A	TO (NDV)
LM139	RM139AJRQMLV	TI	Comp.	H7A0917Z	14P CERDIP
REF05	5962R0051601VPA	AD	Voltage Reference	0428F	8P CERDIP
PM139	5962R8773901VCA	AD	Comp.	1127A	14P CERDIP
RH117	RH117K	LTC	Regulator	0919A	TO-3
RH1014	RH1014MW	LTC	Op-Amp	1307A	FP014
RH1009	RH1009MH	LTC	Voltage Reference	1243A	TO-46

Nine bipolar part types from three manufacturers were selected for this study
All parts are “rad-hard”/ELDRS-free parts

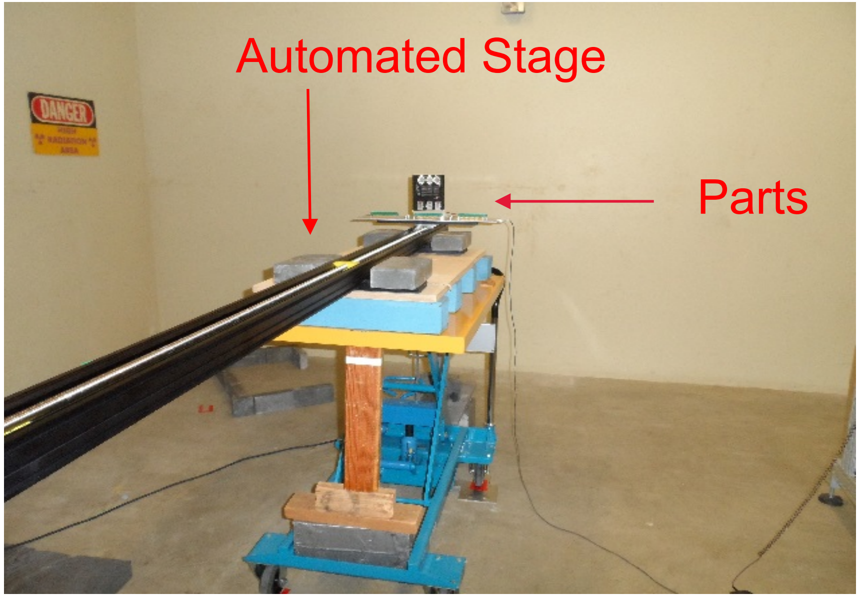
Experimental Details

Four total dose experiments were conducted using JPL ^{60}Co facilities:

- Flight-like variable (pulsed) dose rate (**~6 months**)
- MIL-SPEC low dose rate (10 mRad(Si)/s) (**~1 year**)
- Low dose rate comparable to the rate at which 90% or more of the mission dose is received (**~3 months**)
  - 80 mRad(Si)/s for a representative trajectory, and shielding approach (not the final one)
- High Dose rate (25 Rad(Si)/s)

Comparative tests to 300 kRad(Si) were defined to be able to provide a dose rate recommendation for the RHA test method

Mission Dose Profile Experiments



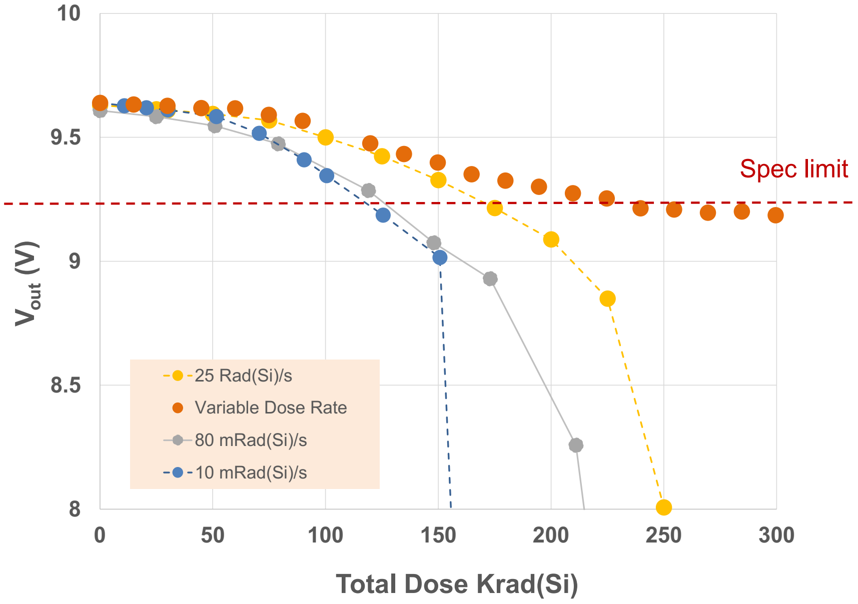
Pulse Dose Profile Selected

Dose Rate (Rad(Si)/s)	Accumulated Dose (Rad(Si))	Time (Hrs)
0.03	1080	10
0.08	1728	6
0.15	3240	6
0.2	2880	4
0.08	3240	6
0.15	1728	6
0.03	1080	10

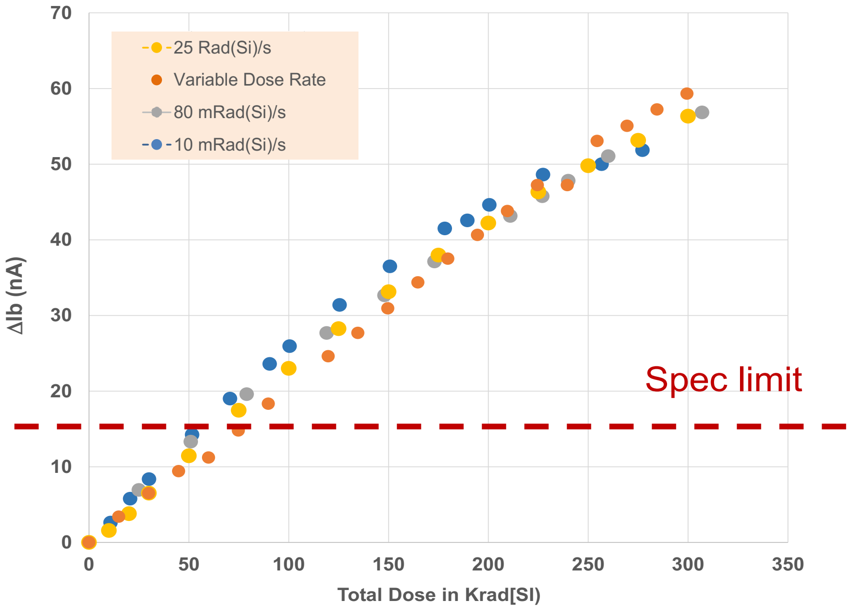
100^0C anneal for 12 hours was used between each simulated flyby to reduce test time from 3 years to 6 months

Experimental Results

RH117 Linear Regulator



RH1014 Op-Amp



Of the nine part types assessed for all conditions, only one part show a functional failure

Experimental Summary

All parts tested@300 kRad(Si) for four dose rate conditions

Parts tested	Functional fail	Fail specifications	Recommended for Europa	Summary
LM124 (TI)	No	Yes	**Yes**	LM124 do not fail functionally @300krad(Si). Degradation shows no dose rate effects and no non-linearities
LM2941 (TI)	No	Yes	**Yes**	RM2941 do not fail functionally @300 krad(Si). Degradation shows a slight dose rate effect.
LM136 (TI)	No	Yes	**Yes**	LM136 do not fail functionally @300 krad(Si). Dynamic Z out of spec <125 krad(Si) LDR. Degradation shows a dose rate effect.
LM139 (TI)	No	Yes	**Yes**	LM139 do not fail functionally @300krad(Si). Ib, Vos goes out of spec < 150krad(Si). Degradation shows No dose rate effects and no non-linearities
REF05 (AD)	No	Yes	**Maybe**	REF-05 do not fail functionally @300 krad(Si). Vref, Vload and Vline, Isource, Isink, Ishort-circuit go out of spec <125 krad(Si)@ LDR. Degradation shows dose rate effects and circuit effects
PM139 (AD)	No	Yes	**Yes**	PM139 do not fail functionally @300krad(Si). Ib, Isink goes out of spec < 200krad(Si).Degradation shows no dose rate effects and no non-linearities
RH117 (LT)	Yes	Yes	**No**	RH117 Fails functionally at125 kRad(Si) @LDR VRline, Vrload, Vout, Dropout, IADJ and Vref go out of spec < 125 krad(Si) @LDR Degradation shows severe dose rate effects.
RH1014 (LT)	No	Yes	**Yes**	RH1014 do not fail functionally @300 krad(Si). Voffset and Ib go out of spec < 70 krad(Si). Degradation shows no dose rate effects and no non-linearities.
RH1009 (LR)	No	Yes	**Yes**	RH1009 do not fail functionally @300 krad(Si). Vref, Load Reg and Dynamic impedance goes out of specs below 150 krad(Si) (LDR). Degradation shows dose rate effects

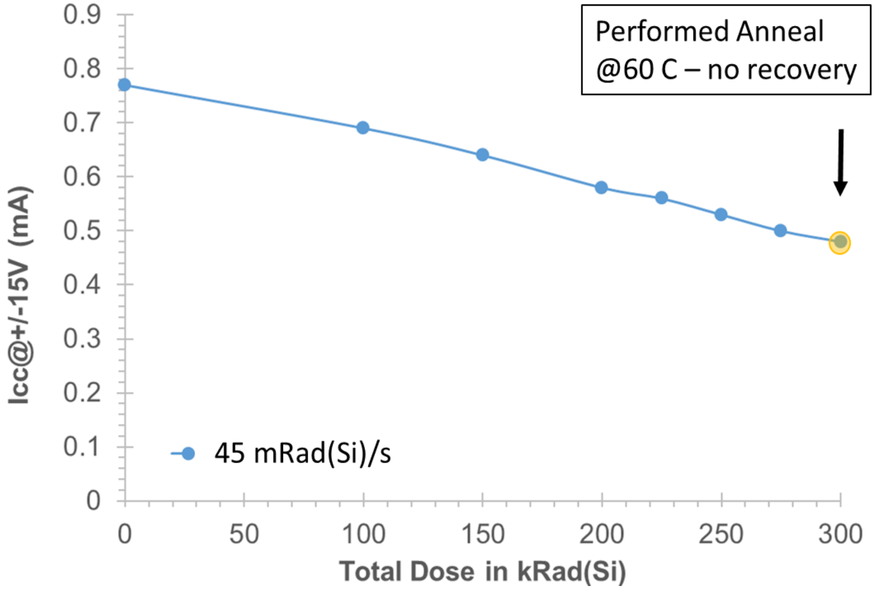
Observations

- All parts see parametric degradation between 100-300 kRad(Si)
- Unlike typical ELDRS-sensitive parts built on non "rad-hard" processes, the 10 mRad(Si) and 80 mRad(Si) data track each for the first 100-150 kRad(Si)
- Very little dose rate effects were observed for the three processes investigated; probably related to the removal of H_2 during processing steps
- Results imply that **10 mRad(Si)/s is overly conservative**
- All the parts behaved very well against the flight-like condition: for most parts degradation was very close to the HDR degradation

Lots of anneal occurred @100^{0}C for these parts for which the degradation should be dominated by interfaces traps

Annealing investigation

Temperature anneal on RH1013 op-amp



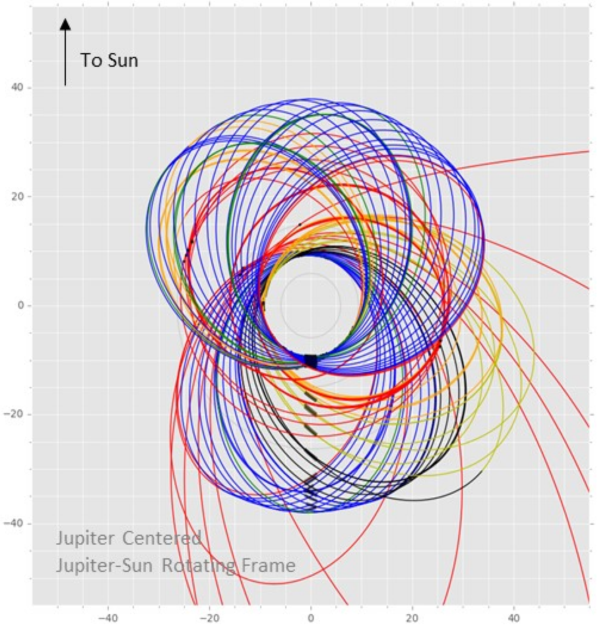
Oxide Traps (N_{ot}) Annealing Law follows an Arrhenius Law

After Saigne et Al. JAP 1997

For N_{ot} (Ea < 1eV), 100 ^{0}C for 12 hours corresponds to about 10-12 days @27C

Typically bipolar parts see their degradation dominated by interface traps (N_{it}). Degradation seems to be dominated by N_{ot} in these new "rad-hard" processes.

Conclusions



- Total dose characterization and RLAT testing for bipolar shall be performed in accordance with:
  - **MIL-STD-883, Method 1019, Condition C:** Average dose rate considering all dose rates above which 90% of the mission dose is received.
  - For the trajectory and shielding approach presented here, the calculated dose rate was 80 mRad(Si)/s and 45 mRad(Si)/s for the new trajectory
  - Or alternatively, MIL-STD-883, Method 1019, Condition D, 10 mRad(Si)/s
- Unlike with ELDRS-sensitive parts, new “rad-hard” processes seem to be dominated by N_{ot} and not N_{it}.
- Consistent with mitigation used by vendors to reduce H_2 contamination in their processing steps.

This RHA method leverages from the unique mission dose-rate profile to bound device performances and reduces test time from 1 year to 80 days

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